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EXPERIMENTAL INVESTIGATION OF LAMINAR TURBULENT TRANSITION AT THE TEST-SECTION WALLS OF A WIND TUNNEL

Yu. V. Lavro and V. M. Filippov

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16. Abstract

An experimental investigation was made of the transition of a laminar boundary layer to a turbulent layer at the side walls of the test section of a low-turbulence wind tunnel. The main statistical characteristics of the transition region (intermittency coefficient and number) were obtained as functions of the velocity of the incident flow and were described by the normal law of distribution of random variables. The investigation was made with the aid of inductive pressure sensors, which made it possible to virtually completely avoid the perturbing effect of the measuring instrumentation on the flow.

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EXPERIMENTAL INVESTIGATION OF LAMINAR TURBULENT TRANSITION AT THE TEST-SECTION WALLS OF A WIND TUNNEL

Yu. V. Lavrov and V. M. Filippov

An experimental investigation was made of the transition of /60* a laminar boundary layer to a turbulent layer at the side walls of the test section of a low-turbulence wind tunnel. The main statistical characteristics of the transition region (intermittency coefficient and number) were obtained as functions of the velocity of the incident flow and the coordinate of the section under study, which were described by the normal law of distribution of random variables. The investigation was made with the aid of inductive pressure sensors, which made it possible to virtually completely avoid the perturbing effect of the measuring instrumentation on the flow.

It is known that vital significance lies in the investigation of the region of the transition of laminar flow to turbulent flow as part of the study of the physical nature of the inception and buildup of turbulence [1], as well as in relation to the practical necessity of knowing the regularities and position of the transitional region in calculating the boundary layer [2, 3]. Recently, interest in these problems has risen owing to attempts to artificially laminarize flow past various parts of flight vehicles.

During these investigations fundamentally new information was obtained concerning the inception and buildup of turbulence after the loss of stability with respect to small flow perturbations. Thus, for example, in [4] the "mottled" nature of

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* Numbers in the right margin represent pagination in the foreign text.

the transitional region of the boundary layer was established. Theoretical substantiation was obtained for the possible existence of a section of laminar flow considerable in extent beyond the stability loss according to linear theory [1]. The conclusions of the papers [5, 1] on the multiple restructuring of laminar flow found experimental confirmation in studies of the transition of the laminar form of liquid flow to the turbulent form by means of the scattered light technique [6].

The aim of the investigation described here was the further accumulation of experimental data on the inception and buildup of turbulence in the transitional region of the boundary layer (the investigation was based on measurements of pressure pulsations at the wall). However, the results obtained can have also applied value in the adjustment and monitoring of the flow field in the test section part of a wind tunnel. /61

The work was done in two stages. The first (preliminary) stage consisted mainly of verifying and elaborating the method and equipment for acoustic measurements of the statistical characteristics of the transitional region of the boundary layer for low flow velocities. In the second stage, a study was made of the regularities of the inception and growth of turbulent patches in the boundary layer at the test-section side walls of a low-turbulence wind tunnel; the intermittency coefficients and number were determined. The primary findings of the study are presented as graphs. The curves obtained were compared with the normal law of distribution of random variables.

Method and Equipment of Experiment

The investigation was conducted in a closed-type wind tunnel. The design and the circuit of the tunnel were first determined by the requirements of a low level of pulsational characteristics of flow in the test section.

With the exception of the metal compartment of the fan and the test section, the housing of the tunnel was made of wood with a sufficiently smooth surface. The cross-section of the prechamber was octahedral. The distance between the opposite faces was 4.5 m. A 3-m long collector ensured a smooth transition from the prechamber to the test section of the tunnel with a flow contraction of 17.6. The investigation was conducted with two deturbulence screens in the prechamber (the first and second from the collector) and with one screen in the last diffusor. All the screens were made of [illegible].3 mm diameter wire with a mesh size of 0.7x0.7 mm. The distance between the deturbulence screens was 0.16 m and the distance from the last screen along the flow to the collector was 4 m. The flaps of the vanes of the guide [illegible] of the fan and of all four bends of the tunnel housing were installed at a zero angle. The test section of the tunnel was square in cross-section, 1x1 m with truncated corners and 1 m in length. The investigation was conducted with angle inserts ensuring a weakly negative pressure gradient along the flow. Each of the side walls of the test section had five ports in which metal dead ends were installed flush with the inner surface. At each dead end, from its external side, four inductive pressure sensors of model DMI-0.1 with 60 micron membranes were installed. One cavity of the sensor communicated directly with the receiving opening in the dead end, 1 mm in diameter, and the second communicated with the flow in the test section through an additional volume and a 0.3 mm diameter micro-opening. The presence of the additional volume and the location of the micro-opening made it possible to relieve the sensor membrane from the action of the time-averaged pressure at the assigned surface point. To amplify the electrical signal of the sensors caused by the pulsational component of the pressure at the wall, use was made of model ANCh multichannel equipment for the carrier frequency. The instantaneous value of the output signals of all channels were recorded on an N-105 slave oscillograph. /62

The coordinates of the points at which the sensors were placed are given in the table.

Sensor nr.	Right, along tunnel wall flow		Left, along tunnel wall flow		Sensor Nr	Right, along tunnel wall flow		Left, along tunnel wall flow	
	x mm	z mm	x mm	z mm		x mm	z mm	x mm	z mm
1	672	−16	674	−15	7	1418	−15	1417	−16
2	783	−0	784	−0	8	1311	−126	1308	−126
3	893	−13	894	−15	9	2008	−16	2006	−16
4	786	−125	784	−126	10	2117	−15	2117	−16
5	1199	−16	1197	−16	11	2228	−16	2227	−16
6	1304	−19	1312	−19	12	2116	−125	2117	−126

The origin of coordinates was chosen in the middle of the sides of the entrance cross-section of the test section; the Ox axis was oriented along the horizontal along the flow; the Oz axis was oriented upwards along the vertical.

The endpiece of a hot-wire anemometer with filament 5 mm from the surface past which the flow was moving was installed at a point with x = 3500 mm and z = 19 mm.

Oscillograms like those shown in Fig. 1 were the basic primary experimental material. By interpreting them, one determined the intermittency coefficient γ and number N, and the inception and growth of the turbulent patches. For an assigned point in the boundary layer and a fixed velocity in the core of the flow, the intermittency coefficient was found as the ratio of the time of observation of the turbulent flow $\sum_{i=1}^{n} \frac{l_i}{v}$ to the total time L/v,

that is, $\gamma = \frac{\sum_{i=1}^{n} l_i}{L}$, where v is the travel speed of the oscillographic tape of the slave oscillograph during the recording of the signal, l_i is the length of the i-th turbulent section on the oscillogram, and L is the total length of the section of the oscillogram being processed. The turbulent section was determined

from the recording of the chaotic signal on the oscillogram. The total length of the oscillogram section being processed (the signal recording time) was selected as sufficiently large for it to have practically no effect on the final value of γ . Examples of the variation of the intermittency coefficient γ as a function of the time τ are shown in the plots in Fig. 1. Based on an analysis of similar plots, the total length of the processed sections of the oscillograms was selected, which for each case corresponded to the signal recording time τ of approximately 80 sec.

The intermittency number was determined from the formula $N = f\delta/u_0$, where f is the mean frequency of changes in the laminar and turbulent regions, and δ is the boundary layer thickness at the point under study (calculated after Blasius).

Main Results of the Experimental Study

Inception and growth of turbulent patches. Even at very low flow velocities (of the order of 1 m/sec), at the end of the test section of the tunnel turbulent patches were induced infrequently along its side walls, which was recorded with the aid of a hot-wire anemometer. As the velocity was increased, the region of the transition of the laminar boundary layer to a turbulent boundary layer shifted upward along the flow. However, the low signal level for low flow velocities and the inadequate sensitivity of the measuring equipment did not permit the tracing of the buildup of the transition region in sections 4 and 5 of the test-section /64
port by the acoustic method. Probably, for this same reason it was not possible to trace the inception and development of the periodic fluctuations in pressure at the test-section walls in the Re number range from loss of stability to the appearance of the first turbulent patches. The recording in the laminar boundary layer of the first well-defined periodic pressure fluctuations virtually coincided with the moment the first turbulent patches detected from the tracings of the chaotic high-frequency fluctuations in a signal of considerable amplitude appeared.

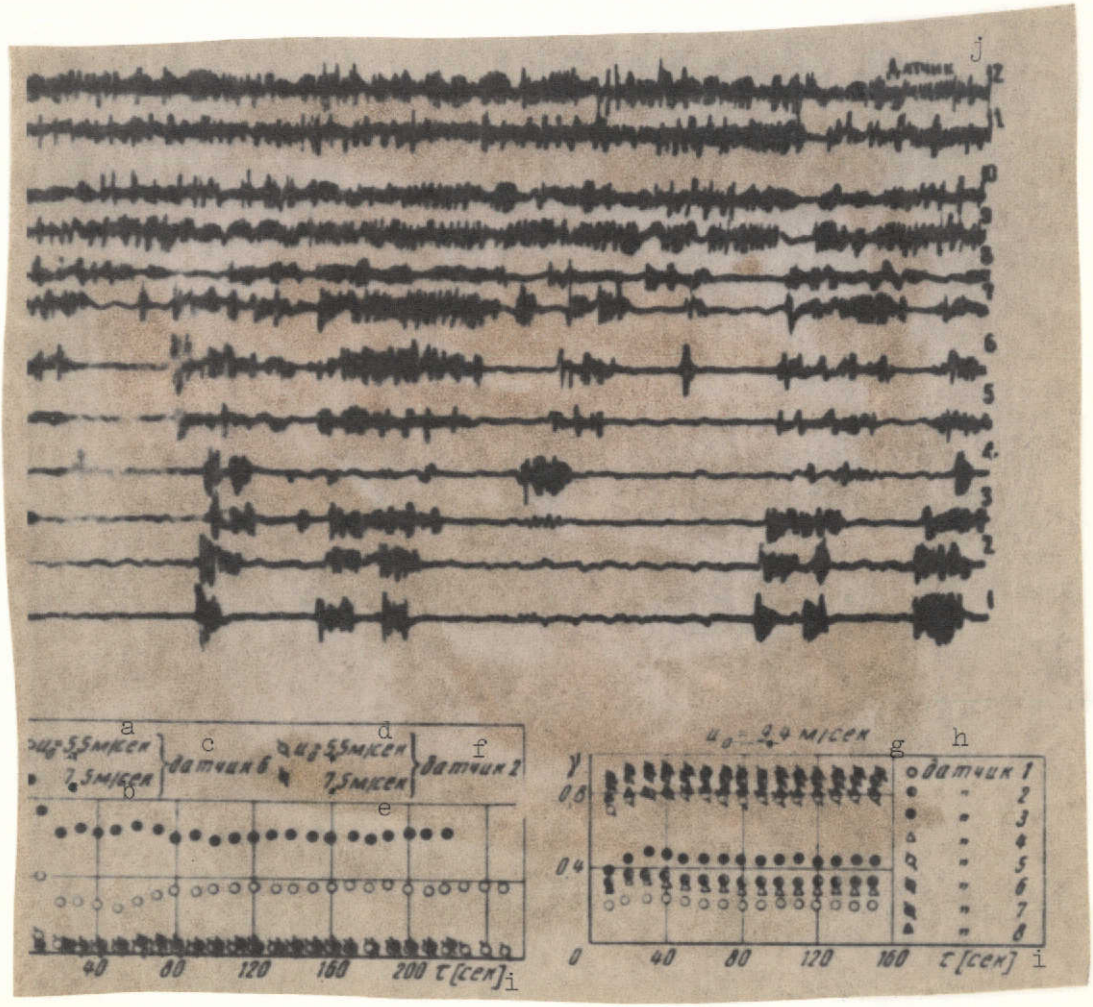


Fig. 1.

KEY: a. u_0 = 5.5 m/sec
b. u_0 = 7.5 m/sec
c. sensor 6
d. u_0 = 5.5 m/sec
e. u_0 = 7.5 m/sec
f. sensor 2
g. u_0 = 9.4 m/sec
h. sensor 1
i. /sec/
j. Sensor

The periodic pressure fluctuations exhibit a number of discrete frequencies. For example, when the flow velocity was 14-17 m/sec, at the points x = 672 mm, z = -16 mm, and x = 893 mm, z = -3 mm, periodic fluctuations were observed with frequencies of approximately 120, 170, and 200 Hz. The inception of periodic fluctuations, entrained downstream, increased in amplitude. Cases were noted when the amplitude of the periodic signals reached the level of the pressure pulsation amplitude in the turbulent patches. Analysis of the oscillograms showed that in most cases, during the period in which the periodic perturbations were alternating between two sensors placed along the flow, their development was climaxed by the formation of turbulent patches. Often the approach of a turbulent patch to a given sensor was accompanied by the initial recording of the periodic signal. Conversely, the conversion of the signal of a patch to a periodic signal was infrequently observed. Perturbations of a periodic character persisted throughout practically the entire transitional region.

Simultaneous recording of the output signals of several sensors made it possible to determine the mean velocity of the leading and the trailing edges of a patch between two sensors. The velocities obtained for various patches differed widely, which was probably due to the displacement of the patches in the flow with different degrees of perturbation and by the merger of a patch with newly formed patches along the route between two sensors. It can be assumed that the lowest velocity for the leading edge of a patch and the largest velocity for the trailing edge will correspond to the displacement of a patch in an unperturbed flow without merger with other patches. These limiting velocity values of the leading and the trailing edges proved to be equal to approximately 90 and 54 percent of the velocity of the incident flow, which practically coincided with the values obtained in [7]. However, an analysis of a large volume of experimental material indicates that in the transitional region the growth of turbulent patches differs from the situation presently described

in the literature. Probably, owing to the perturbation of the main flow in the transitional region the turbulent patches are random in shape. Being swept downstream, the patches unevenly increased along all sides, joining up with each other in areas. At the end of the transitional region there were now encountered laminar regions whose area decreased with time both owing to the arrival of turbulence across the entire perimeter, as well as due to the inception of new turbulent centers.

Intermittency coefficient. The intermittency coefficient γ is the most common quantitative characteristic of the development of the transitional region of a laminar boundary layer into a turbulent.

The values of γ obtained and the corresponding velocities /65 of the incident flow u_0 were first plotted on probability paper. This paper has along its Y axis a scale proportional to the probability that a random event will appear under the normal distribution, and along its X axis -- a linear scale [8]. As expected [6, 7], in the plots the function proves to be near-linear, which evidences the normal (or near-normal) distribution law

$$\gamma(u_0) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^{u_0} \exp\left[-\frac{(u_0 - \bar{u}_0)^2}{2\sigma^2}\right] du_0. \qquad (1)$$

The parameters $\bar{u}_0$ and σ characterizing the center and dispersion of the distribution were determined by the usual means from these same plots: $\bar{u}_0 = u_{0,\,\gamma=0.5}$, and $\sigma = 0.5\,(u_{0,\,\gamma=0.16})$ for each point of the surface swept by the flow we are considering. The values found for the quantities $\bar{u}_0$ and σ were used in plotting their reciprocals as functions of x (Fig. 2). From the plots in Fig. 2 the following experimental dependences of $\bar{u}_0$ and σ on x were obtained:

$$\left.\begin{aligned} \bar{u}_0 &= \frac{14{,}1}{x+0{,}2}, & \sigma &= \frac{4{,}0}{x+0{,}2}; \\ \bar{u}_0 &= \frac{10{,}3}{x+0{,}1}, & \sigma &= \frac{3{,}2}{x+0{,}1} \end{aligned}\right| \qquad (2)$$

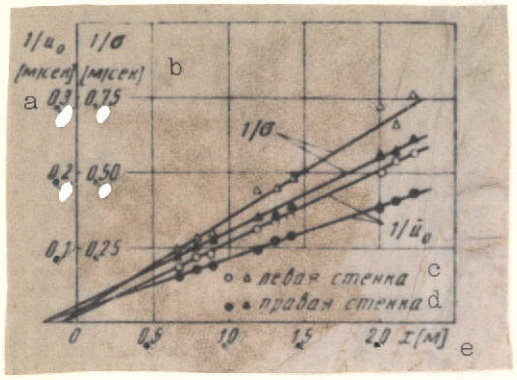


Fig. 2.
KEY: a. [m/sec] b. [m/sec]
c. left wall
d. right wall
e. [meters]

for the right and left walls of the tunnel test section along the flow, respectively. These results show that throughout the range of velocities u_0, the transitional Re numbers and the extent of the transitional region retained their constant values along each of the walls: The conditional origin of the laminar boundary layer was shifted upward along the flow from the entrance section of the test section by approximately 0.2 and 0.1 m for the right and left walls, respectively. The transition at the left wall (external side of the circuit of the wind tunnel) commences at somewhat smaller velocities u_0 than at the right, which possibly was caused by the influence of flow prehistory.

The experimental expressions obtained for the values of $\bar{u}_0$ and [illegible] make it possible to calculate the value of γ for the assigned values of u_0 and x. Fig. 3 presents the experimental values of γ as a function of u_0 for all the points studied, located approximately along the central line of the walls. The experimental points fitted fairly closely along the continuous curve calculated according to Eq. (1), with reference to Eq. (2). The results of the experiments, after being normalized by being reduced to the translation of the origin of reference [illegible] center $\bar{u}_0$ of the distribution and to selection as the unit of the scale [illegible] (that is, $t = \frac{u_0 - \bar{u}}{\sigma}$) lie on the same /67

curve. Fig. 4 presents, in the previous symbols, the function $\gamma = f(t)$ plotted on probability paper for the left and right sides of the tunnel test-section. In the calculations of t, use was

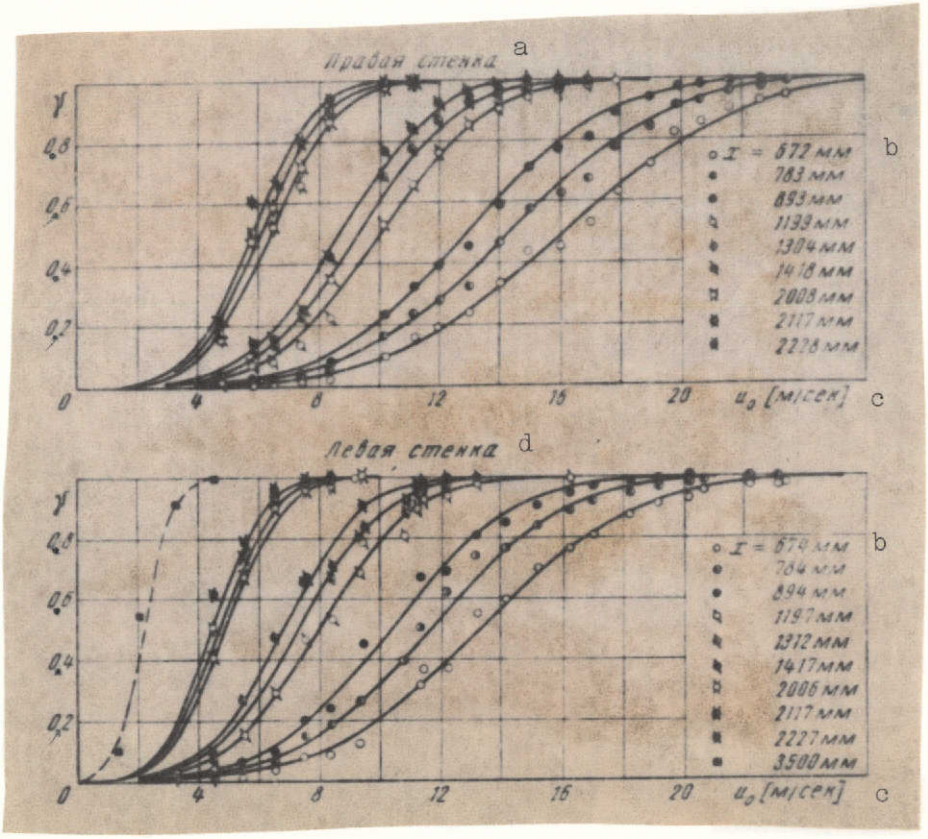


Fig. 3.

KEY: a. Right wall b. mm
c. /m/sec/ d. Left wall

made of the experimental values of u and σ. The experimental points grouped around the curve

$$\gamma(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{t} e^{-\frac{t^2}{2}} dt,$$

which practically did not extend beyond 95 percent of the boundary (dashed lines) of the random dispersion, though the extremal points (especially for small γ) deviated somewhat from the line.

The measurements made with sensors 4, 8, and 12 situated roughly 126 mm below the mid-line of the sides yielded a somewhat larger scatter of results, which was especially true of the left wall.

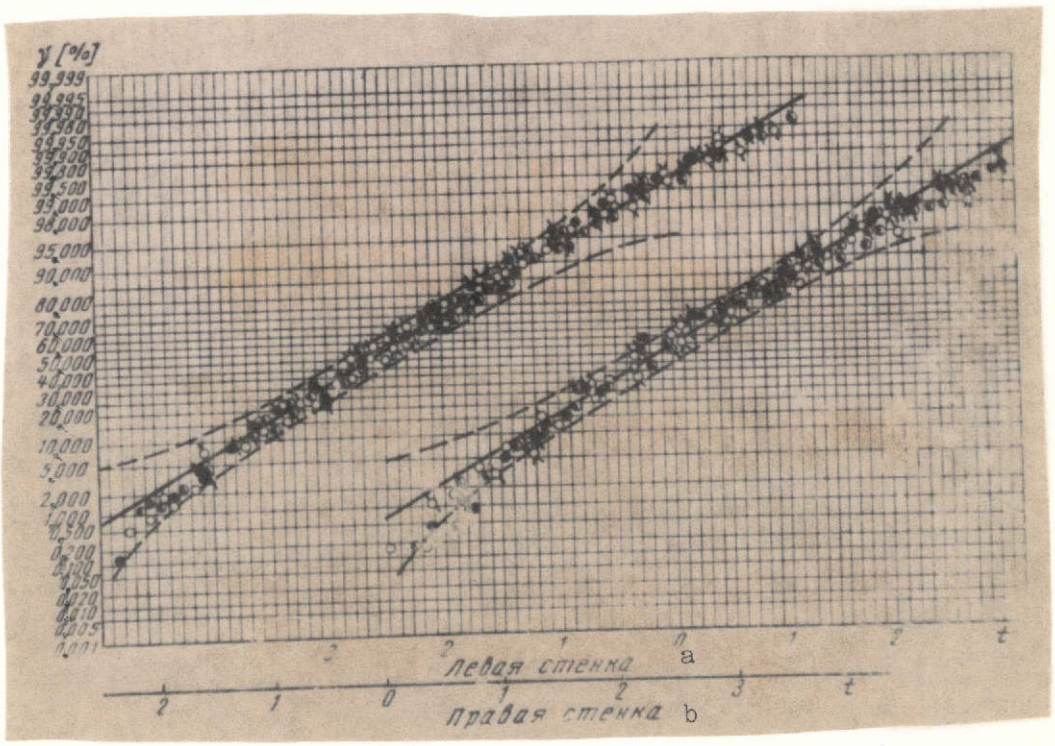


Fig. 4.
KEY: a. Left wall b. Right wall

Intermittency number. The region of transition of a laminar boundary layer into a turbulent boundary layer, along with the coefficient γ is described by the intermittency frequency N.

Fig. 5 presents the values of mN (m = normalizing cofactor) as a function of the previously introduced dimensionless parameter $t = (u_0 - \overline{u}_0)/\sigma$. The value of m for each sensor was determined by using the least-squares method [9]. The distribution of the intermittency number with respect to velocities roughly obeys the normal law of distribution of probability density (solid curves). However, the scatter of the experimental points is more substantial than the scatter of the corresponding values of the intermittency coefficient.

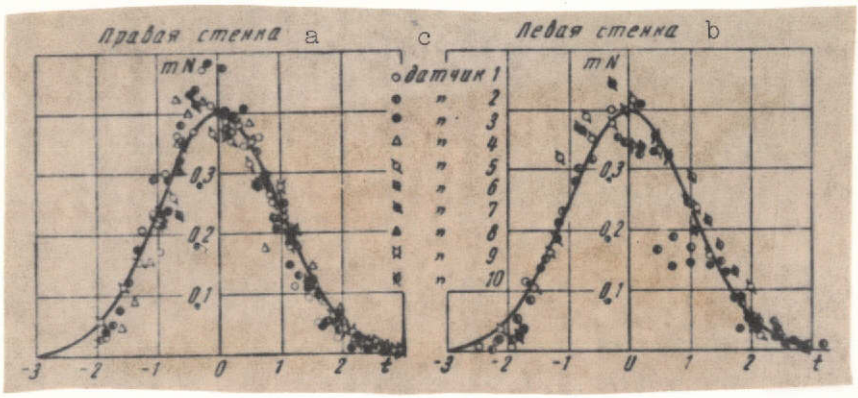
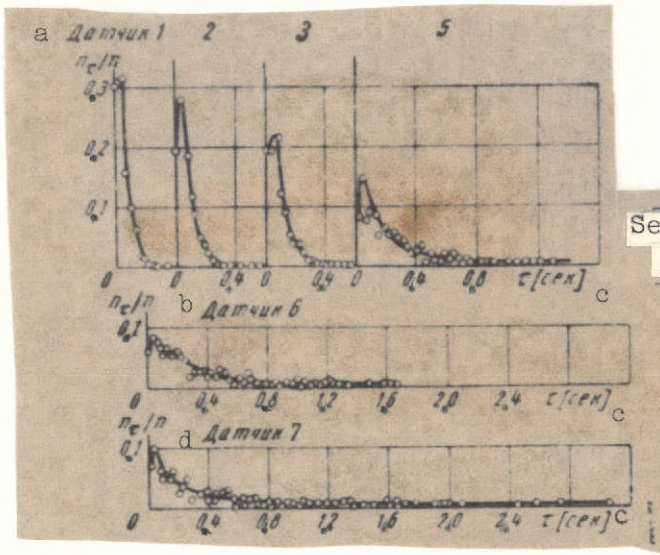


Fig. 5.

KEY: a. Right wall b. Left wall
c. Sensor

The intermittency number makes it possible to judge the mean duration of the turbulent patches. An idea of the size distribution of the patches is given by Fig. 6, where along the X axis is plotted the middle of the i-th interval of the temporal extent of the turbulent patches τ_i at a fixed point in the boundary layer, and along the Y axis is plotted the relative number of patches with temporal extent in the interval $\tau_i \pm \frac{\Delta\tau}{2}$. The temporal interval $\Delta\tau = 0.03$ sec. The measurements were made along the left wall with sensors 1-3, and 5-7 at incident flow velocity $u_0 = 0.4$ m/sec. The recording time was approximately 2.5 min. For sensor 7 the two extremal experimental points corresponding to $\tau_i = 4.08$ and 4.67 sec were not plotted on the graph. /68

From the plots in Fig. 6 it is clear that at a given incident flow velocity u_0, the displacement of the observation point downstream along the transitional region is accompanied by a significant broadening of the temporal range of turbulent patches encountered and by a decrease in the maximum value of n_τ /n. For example, when x = 674 mm, the longest time during which an individual turbulent patch flowed was about 0.37 sec, while when x = 1417 mm, this time was 4.7 sec. The values of n_τ /n reached a maximum in the range of small patch dimensions.



Sensor nr.	x [mm]	τ	n
1	674	0,22	508
2	784	0,340	588
3	894	0,45	666
5	119	0,775	474
6	1312	0,875	338
7	1417	0,91	270

Fig. 6.

KEY: a. Sensor 1
b. Sensor 6
c. [sec]
d. Sensor 7

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